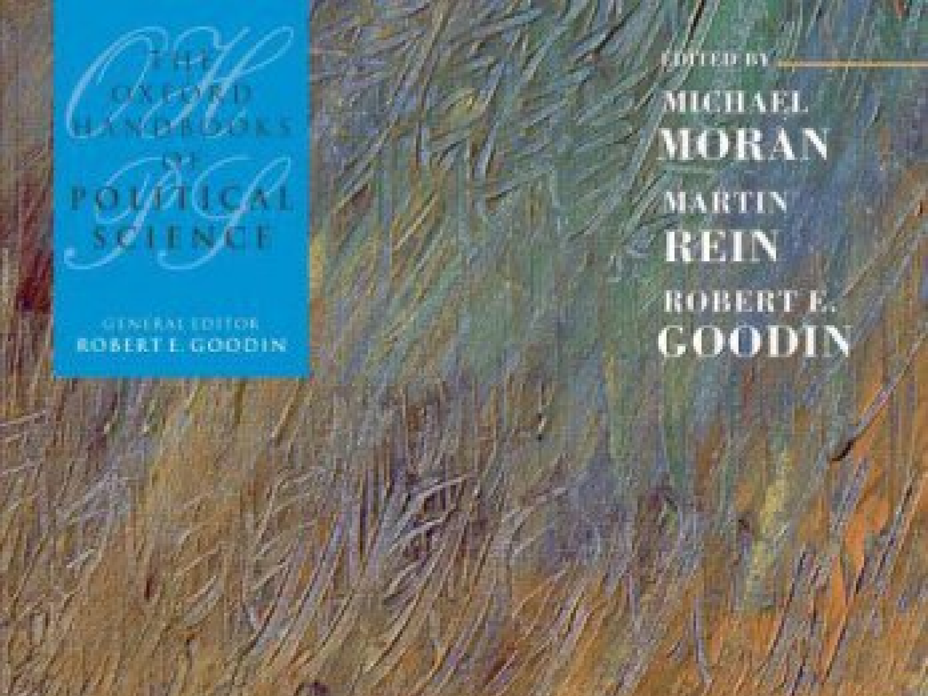

THE OXFORD HANDBOOKS OF POLITICAL SCIENCE

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1. The Context: Nuclear Weapons and US Strategic Nuclear Beliefs

The policy process can be conceived of as a flow where US nuclear weapons policy and forces are determined in broad outline by presidential, National Security Council, and Defense Secretary directives. The president and NSC also direct policy analysts to study alternative options. Presidential and NSC directives are then fleshed out and implemented by planners and analysts within the Defense Department and the military services. In both official and public discourse, the lingua franca of nuclear arguments was of course deterrence theory, but arguments rested on nuclear modeling—operations research and systems analysis techniques. United States strategic nuclear policy ranged from war fighting to deterrence (Freedman 2003; Glaser 1990; Eden and Miller 1989). The dominant logic of deterrence theory is based on the idea of keeping someone from acting by threatening them with painful punishment if they do act. The Soviet Union, it was supposed, would be deterred from attacking the United States, or its more distant interests, if they knew the United States would attack them in return. The belief was that decision makers would *not* be deterred if they thought they could get away with an attack without being punished or if the punishment were very light. Success in deterring an attack depended on one ensuring that the other side knew that they would, most likely, receive unacceptable damage as retaliation for an attack.

This logic of deterrence and credibility is embedded in other intersubjectively held philosophical, instrumental, normative, and identity beliefs. The core beliefs of nuclear "rationality"—that the Soviets were the enemy, that the best way to deal with them was through threats, that the utility of threats depends on an ability to carry them out, and so on—were rarely challenged. At the beginning of the cold war, the idea of killing tens of millions of the other's populations was acceptable, considered necessary to ensure the survival of one's own state and population—though by the mid-1970s the US government argued that it was not targeting civilian population per se (Ball 1986*a*, 27). In addition to these core beliefs there were many more context-specific beliefs about how deterrence worked and how to structure nuclear forces so that threats were credible, and so that if war came the mission of destroying the other side could be accomplished (Jervis 1984; Kull 1988). The project of constructing a nuclear arsenal for the United States in part consisted of meeting the "requirements" of deterrence in a nuclear world. Part of the requirement for deterrence during the cold war was to acquire a secure second strike capability—that is, to build enough weapons that could survive a Soviet first strike nuclear attack, and that would be able to retaliate against their cities or remaining nuclear weapons to inflict unacceptable damage.

There were also those who pushed for the United States to develop a nuclear war fighting capability. Indeed, early US nuclear strategy was explicitly focused on developing a capability for pre-emptive nuclear war fighting, targeting Soviet and Chinese conventional military forces and their industrial infrastructure (Rosenberg

1986, 40, 49; CBO 1978*a*). The USA also acquired weapons that were accurate enough to destroy Soviet nuclear weapons. But, some strategists argued, the USA had to be careful not to build so many of these accurate weapons as to put the Soviet Union in fear that the USA was preparing to attack its weapons and thus vitiate the Soviet Union's ability to deter a USA attack. If the Soviets believed that the USA was planning to strike first and could destroy their weapons (and their ability to the deter the USA), the Soviets might launch their weapons out of the fear of losing them to a US first strike. According to this reasoning, each side must build enough weapons to survive a first strike by the other side, but not so many extremely accurate weapons as to scare the other side into launching a pre-emptive nuclear strike. If both sides had highly accurate weapons, and a policy of aiming them at the other's weapons, a reciprocal fear of surprise attack could be an incentive for both countries to put their nuclear weapons on alert, and perhaps lead to nuclear war. The dilemma of creating a secure second strike force with highly accurate warheads was perhaps most acutely posed during the late 1970s and throughout the 1980s in the "window of vulnerability" debate and by critics of US acquisition of highly accurate land-based MX and submarine-based Trident D5 missiles.

Those charged with developing nuclear weapons, and the external critics of US strategic nuclear policy, sought to make sure that the nuclear policy was rational. By rational they meant that the most cost-effective and survivable weapons were purchased, and that those weapons sent the intended signal to the adversaries of the United States. But there were frequent and often bitter disputes within the armed forces and the Pentagon, among civilian defense analysts, and in the United States Congress about how to best implement nuclear strategy. After 1961, a consensus emerged within the strategic analytical community that the best method for ensuring that the posture was rational, and to constrain procurement by military services, was to use operations research and systems analysis.

2. Origins and "Philosophy" of Strategic Nuclear Systems Analysis

Operations research is now widely applied to all sorts of decision problems, as is evident in the journal of the Operations Research Society. Its origins, however, are in a set of mathematical techniques applied by United States and British military analysts during the First World War and applied more widely during the Second World War to improve the efficiency and effectiveness of strategic bombing and anti-submarine warfare (O'Neill 1993; Quade 1968*a*; Hitch 1965; Freedman 2003 167). After the Second World War, many of the techniques that would become nuclear systems analysis were refined by analysts at the RAND Corporation think tank and at the Strategic Air

Command (SAC) of the air force.[16] Early nuclear modelers relied on the analysis of the effects of nuclear weapons against Hiroshima and Nagasaki, and on data gathered through nuclear weapons tests in the South Pacific and the far West. The public rarely saw those early studies, though they sometimes came to light in popular books such as Herman Kahn's *On Thermonuclear War* (1960).

Systems analysis became a dominant tool in the Pentagon under Kennedy's Secretary of Defense Robert McNamara who hired operations researchers, economists, and RAND Corporation strategists to form the Systems Analysis Office at the Department of Defense in 1961. McNamara "made it clear at the outset that . . . he wanted all defense problems approached in a rational and analytical way, and that he wanted them resolved on the basis of national interests" (Enthoven and Smith, 1971, 31). McNamara's "whiz kids," the bright young men who did the systems analysis for the Pentagon, immediately set about "rationalizing" the different services' military forces, which included eliminating some of the military's favorite programs and weapons. They often won arguments, or at least set the terms of the debate within the Pentagon about nuclear forces, because their analysis seemed more objective and rational than other arguments that the services could put forward. This fact was said to annoy members of the military services who wanted to acquire the weapons they wanted without outside interference. According to Fred Kaplan, "In December 1961, some of the brightest Air Force officers met at Homestead Air Force Base . . . to figure out what they were doing wrong, how they could deal with McNamara and win a few bureaucratic battles. They concluded that they would have to work up their own analytical corps. . . . They too would have to learn the lingo of 'scenarios,' do 'cost-effectiveness' analysis, become their own 'systems analysts' " (Kaplan 1983, 256–7). Thus, the use of systems analysis techniques became essential for analysis of nuclear planning and war inside the Pentagon, as well as at the think tanks which evaluated nuclear strategy.

Basic criteria for the US nuclear arsenal were set and/or evaluated using systems analysis. For example, in the early 1960s, McNamara articulated the requirement that the United States be able to accomplish "assured destruction" of the Soviet Union even after the USA suffered a nuclear strike by the USSR. US strategic planners "calculated that the Soviets would be sufficiently deterred if we could kill 30 percent of their population and destroy half of their industrial capacity, and further that the task could be accomplished with the explosive power of 400 megatons" (Kaplan 1983, 317). In 1967, McNamara reduced this "requirement," arguing that the United States would have the capacity to "inflict an unacceptable degree of damage . . . even after absorbing a first strike" with 200 equivalent megatons[17].

[16] As Rosenberg notes, "The JSCP [Joint Strategic Capabilities Plan of 1952] and the operational plans it guided including the SAC Emergency War Plan, were prepared consistently on an annual basis. They fostered a process of debate and analysis that, in the absence of real global conflict, served as a kind of 'surrogate war' for generating and testing forces and concepts." In this context, "Each new planning effort built on the experience gained in the preceding 'war,' thereby creating a dynamic that tended to discourage radical changes" (Rosenberg 1986, 43).

[17] McNamara quoted in Salman, Sullivan, and Van Evera 1989, 209; see also Enthoven and Smith 1971, 207; and Kaplan 1983, 317 18.

The Systems Analysis Office prepared the initial “Draft Presidential Memorandums” (DPMs), on issues such as strategic offensive and defensive nuclear forces, tactical nuclear forces, and anti-submarine warfare. The process of drafting the final DPMs, which would serve as the basis for decisions by the Secretary of Defense and the president, included input and review by all the relevant parties within the DOD over several months. Two former members of McNamara’s systems analysis team described the DPM procedure this way. “The growth in the number of DPMs reflected McNamara’s desire to have all major defense programs considered and analyzed as a whole. This is a good illustration of what we like to call ‘McNamara’s First Law of Analysis’: always start by looking at the grand totals” (Enthoven and Smith 1971, 54). They urged systems analysts to keep the larger context in mind:

> Whatever problem you are studying, back off and look at it in the large. Don’t start with a small piece and work up; look at the total first and then break it down into its parts. For example, if cost is the issue, look at total system cost over the useful life of the system, not just at this year’s operating or procurement costs.... If you are analyzing a particular strategic offensive weapon system, start by looking at the total strategic offensive forces. If you are considering nuclear attack submarines, look at the total anti-submarine warfare force, which includes land- and sea-based patrol aircraft, destroyers, sonars and the like. One simply cannot make sense out of costs, or missiles, or submarines without looking at the totals. The DPMs were a practical result of this principle. (Enthoven and Smith 1971, 54)

The DPMs drew on the work of systems analysis in order to evaluate the competing claims of different actors and devise policy, and calculations were fed into the protocols for nuclear weapons use, the Single Integrated Operational Plan (SIOP). Enthoven and Smith describe systems analysis as a “frame of mind” and a “philosophy:”

> Systems analysis is a reasoned approach to highly complicated problems of choice in a context characterized by uncertainty; it provides a way to deal with differing values and judgments; it looks for alternative ways of doing a job; and it seeks by estimating in quantitative terms where possible, to identify the most effective alternative. It is at once eclectic and unique. It is not physics, engineering, mathematics, economics, political science, statistics or military science; yet it involves elements of all these disciplines. It is much more a frame of mind than a specific body of knowledge.... A good systems analyst is a relentless inquirer, asking fundamental questions about the problem at hand.... systems analysis is more a philosophy than a specific set of analytical techniques. (Enthoven and Smith 1971, 61–2)

Operations research and systems analysis applied to nuclear war became a form of nuclear reasoning or rationality, but there was more than one way to analyze nuclear problems. The Joint Chiefs of Staff “Catalogue of Wargaming and Military Simulation” notes eight models which could be used to assess the specific effects of nuclear weapons, estimate civilian fatalities from nuclear war, or model a full-scale nuclear war (Arkin and Fieldhouse 1985, 99). Game theory, computer simulations, and war gaming (where live military forces engage in mock battles under conditions that partially replicate those of a war) are also used to understand the utility of particular forces and strategies against potential adversaries. What is described in this chapter is thus only a snapshot of the use of modeling for nuclear weapons issues.

3. BASIC SYSTEMS ANALYSIS TECHNIQUES

Policy modelers are always responding to a problem. In the case of nuclear weapons and nuclear war, the problem is typically understood as a scenario. War scenarios are the political and military conditions in which the system under analysis is assumed to be operating. For example, one classified study produced by the Pentagon's Director of Defense Research and Engineering for Secretary of Defense McNamara considered the problem of damage limitation: "If the Soviets spend *x* dollars to create damage in the U.S., and the U.S. spends *y* dollars to limit damage, what is the percentage [*sic*] U.S. population and industry surviving? What are the results of the mirror imaging problem? (Note: Soviet 'damage limiting' is the same problem as U.S. 'assured destruction.' [*sic*])" (Director of Defense Research and Engineering 1964*b*, 14). Other strategic nuclear war scenarios consider using nuclear weapons and the force posture for deterrence or using the weapons to wage a nuclear war should deterrence fail. War fighting scenarios may be "first strike" or "second strike" and they also vary depending on whether the targets are other nuclear weapons or conventional forces (counterforce) or cities and industry (countervalue). Charles Hitch illustrates one use and technique of systems analysis: "To give an oversimplified example, suppose the objective were to achieve an expectation of destroying 97 per cent of 100 targets, using missiles having a per cent single-shot 'kill' capability." He continues:

> The traditional requirements study would conclude that 500 missiles were needed because 100 missiles would achieve an expectancy of 50 kills, 200 missiles 75 kills, 300 missiles 87 kills, 400 missiles 94 kills, and 500 missiles 97 kills. This, of course, merely reflects the operation of the familiar law of diminishing returns. But the significant point is that the last 100 missiles would increase the "kill" expectation by only three extra targets, from 94 to 97. Thus we should not only ask the question, "Do we need a capability to destroy 97 percent of the 100 targets?"; we should also ask the question, "Is the capability to raise expected target destruction from 94 to 97 percent worth the cost of 100 extra missiles?" In other words, we must not examine total costs and total products but also marginal costs and marginal products. (Hitch 1965, 50 1)[18]

The particular numerical values used to conduct systems analysis include the quantification of nuclear weapons effects, the capabilities of the weapons and their strategic "delivery vehicles" (aircraft or missiles), and the characteristics and "value" of the target. Table 38.1 summarizes some of the characteristics and their units that are commonly used in basic systems analysis equations that deal with nuclear exchange scenarios.

Analysts also want to know how likely it is that, once launched, the warhead delivered by a missile or aircraft will be able to destroy its intended target. The formulas used to estimate the likelihood of one of these events, and even of a number

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[18] For example, multiply the number of targets remaining by the SSPK of the missiles. Then add the number of targets killed after each round. If one cannot count on knowing which missiles were successfully destroyed in the first round, one must continue to send missiles to all of the targets.

Table 38.1 Basic inputs for nuclear modeling

Type of information	Characteristic measure	Acronym/symbol
Nuclear explosion effects	blast overpressure	psi: pounds per square inch
	heat/thermal radiation (prompt)	temperature calories per square
	long-term radiation	centimeter cal/cm^2
		REM and RAD[a]
		half life in years
Weapon capabilities	delivery vehicles	DV
	missile re-entry vehicles	Rv
	accuracy	CEP: circular error probable in nautical miles or feet; the radius from the target that a re-entry vehicle would land with 50% probability
	yield in megatons TNT equivalent	Y in MT and EMT (scaled to 1MT) where EMT = Y2/3 for yields < 1MT and EMT= Y1/3 where Y is >1MT
	overall reliability	OAR or R
Target characteristics	hardness	H in pound per square inch or psi
	type: area (e.g. city, airbase, factory) or point (missile) or linear (railroad track or road)	

Note: see Glasstone and Dolan 1977 for a more comprehensive discussion of nuclear weapons effects.

[a] A rem (reontgen equivalent man) is a measure of biological damage; a rad is a measure of radiation energy absorbed.

of these events, are derived from nuclear weapons test data and from commonly used statistical procedures. One basic problem, of determining the probability of a single nuclear weapon of a certain size destroying a target of a certain size and type, is symbolized in the following formula known as the “single shot kill probability” or SSPK formula: $SSPK = 1-0.5(LR/CEP)^2$ where LR or lethal radius is the radius of (blast) destruction of a warhead (measured in nautical miles) of a certain yield against targets of a particular hardness and CEP is the measure of the warhead’s accuracy.[19] If the hardness of a particular target is given as greater than 1,000 psi the lethal radius formula would be:

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[19] A nautical mile is longer than a standard mile: 1 nm 6,080 ft; 1 mi 5,280 ft.

$$LR = \frac{2.62\ Y^{1/3}}{H^{.33}}$$

and if hardness were about 5 psi, the LR formula would be:

$$LR = \frac{6.81Y^{2/3}}{H^{.62}}$$

where Y is Yield in equivalent megatons and H is hardness in pounds per square inch. Overall probability of kill or OPK, is calculated by the equation: OPK = SSPK (OAR) where OAR is the overall reliability of the missile delivery vehicle and warhead. In other words, to determine how likely it is that a nuclear weapon will be able to destroy any particular target, one must determine the destructive capacity of a weapon against a target of a certain hardness, where hardness is the target's ability to withstand the blast effects of a nuclear weapon. For example, each United States MX missile has ten nuclear warheads, each with a yield of 0.45 equivalent megatons and an estimated accuracy of 0.06 nautical miles CEP. The overall reliability of the MX missile delivery vehicle and warhead is often assumed to be 0.81 per cent. The greater the hardness of a target, the less likely it will be destroyed by the blast effects of a nuclear weapon. However, the greater the accuracy and destructive power of a warhead, the more likely that a single shot will destroy the target.

Modeling a nuclear war would involve assessing the probable outcome of using one side's nuclear weapons against another side's nuclear weapons and cities and other targets. This requires figuring out how a number of weapons would perform against many targets and whether more than one nuclear weapon should be used against a particular target to increase the likelihood that the target would be destroyed. And of course it is possible to model a dynamic exchange of weapons between two or more sides assuming various constraints, such as the use of ballistic missile defenses and so on. The results of these calculations are then used in arguments about whether one side's nuclear forces and strategy are adequate for the task (deterrence or war fighting) or whether some change in forces or strategy would be required to meet the task (e.g. see CBO 1978*a*). The term "damage expectancy" (DE) describes the "probability that the desired level of damage will be achieved against each target or set of targets" and consists of the product of individual probabilities that systems function reliably (PRE), of prelaunch survivability (PLS), of penetrating air defenses (PTP), and the probability of killing the target (PK). Thus, $DE = PRE \times PLS \times PTP \times PK$ (Postol 1987, 379–80). The CBO (1978*b*, 52) used a different equation for Damage Expectancy: "Mathematically, $DE = 1 - (1 - R \times Pk)^n$." Where R is reliability, P is the probability of successful penetration to target, and n is the number of nuclear weapons of the same type allocated to the target. Other basic formulas and procedures for calculating the activities of nuclear war are dependent upon particular scenarios and target sets. Common scenarios for nuclear war fighting are "area barrage" (against a large area), "linear barrage" (against a linear target such as a railway), "defensive" (where weapons are to be defended against attack), and "counterforce exchange" (targeting each other's nuclear weapons). The assumptions, data, and formula given above are thus intended as simple illustrations for what can be a much more involved and intricate set of calculations.

4. Rational Representation or Social Practice?

The aim of nuclear operations research and systems analysis was to help nuclear strategists make decisions about which weapons to acquire, how to use the weapons, and how to predict how others will likely use their weapons. Practitioners believed that their analysis represented the *realities* of nuclear weapons and war. Indeed, the equations and models seem straightforward enough. And getting the numbers or parameters to put into the equations also seemed simple enough: just do the tests or make observations of the phenomena. Yet practitioners themselves noted that systems analysis regularly suffered from several problems: opaqueness, uncertainty, arbitrariness, and unrealistic scenarios. Thus, the policy modelers, and their critics cautioned that there were limits to individual analyses and to the craft.[20] As noted below, the proposed solution of the practitioners' systems analysis was to ameliorate and correct these problems through better analysis—to make the models more transparent, certain, realistic, and complete. Yet correcting the problems would not necessarily result in better policy modeling. Insiders believed that if the problems discussed below were corrected the models could ultimately accurately model the nuclear world. Yet, something more fundamental emerges when we examine the practice of systems analysis from outside the paradigm. No amount of tinkering could make the systems analysis better for purposes of policy modeling. The nuclear world was not simply re-presented and understood in and through a neutral and scientific policy-modeling process. Rather, nuclear systems analysis itself in part made and remade the nuclear world. As the following discussion of the problems of opaqueness, certainty, omission, arbitrariness, and implausibility shows, the models and abstractions made an already elusive nuclear world more opaque, uncertain, and arbitrary.

Opaqueness. Transparency of assumptions and techniques facilitates informed assessments and criticism of the policy process. Perhaps the most common criticism of systems analysis and other techniques of military assessment is that the practitioners have not made their assumptions and procedures transparent so that others (including other experts) can fully understand and evaluate their work. Opaqueness

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[20] Quade (1968*b*) summarized several other "pitfalls" that can confound systems analysis such as the failure to specify the problem, adherence to cherished beliefs, parochialism, disregard of the limitations of forces available, and so on.

may also be consciously adopted as a cover for extreme biases in analysis that are used to advance a particular interest (Salman, Sullivan, and Van Evera 1989). In discussing military analysis techniques, models, simulations, and games (MSG), Garry Brewer and Martin Shubik (1979, 225–6) argued that "all such analyses are generated by a program, the workings of which are obscure and often unfathomable... [T]he interested onlooker does not know, for instance, what the structure of the MSG is, what data are assumed to be relevant, what is omitted, what factors influence which others, or how sensitive the outcome is to changes and uncertainty in the assumptions." Like most conscientious scholars and consumers of systems analysis, Brewer and Shubik urge practitioners to make their assumptions and operations "less opaque" and to produce alternative analyses based on "equally plausible assumptions about the performance of weapons and the operational environment." Of course this last piece of advice presumes that there are such things as more or less plausible assumptions and scenarios.

Certainty and uncertainty. Systems analysis is specifically intended to model decisions in uncertainty. Systems analysis relies on pre-existing data for inputs and makes assumptions about probabilities of uncertain events. All policy modeling is therefore more or less sensitive to degrees of certainty and uncertainty.[21] Yet, Quade (1968*b*, 356) has noted that systems analysts sometimes neglect "consideration of the real uncertainties" and focus on uncertainties that have been modeled or simulated although "real uncertainties may have made trivial the effect of any statistical uncertainty." More fundamentally, because of the nature of nuclear weapons and nuclear war, it may not be possible for nuclear systems analysts to even know the degree of uncertainty they are attempting to model. Despite their best efforts to represent, specify, and bracket the range of possible outcomes and uncertainties, analysts were ultimately working in a realm of illusory or even false certainty. Thus, numbers were used as if they were hard, when in fact the values were quite uncertain. Specifically, the numbers used to describe nuclear weapons and their effects—such as hardness, CEP, and reliability—are assumed to be "hard," based on real, observable, and knowable data. Yet, several basic inputs are not hard at all in the sense of being observable and knowable with high degrees of certainty because data used for input are derived from tests under "artificial" conditions that do not approximate the real conditions of nuclear war. Analysis assumed the numbers were "real;" rather, the data that comprised the assumptions and values used in systems analysis were social constructions.

For example, hardness, that is, the ability of an object to withstand the effects of a nuclear weapon to a designated level of blast overpressure, is a crucial input to equations in nuclear systems analysis; results are often quite sensitive to changes in the hardness parameter (recall that $\mathrm{SSPK} = 1 - 0.5(\mathrm{LR}/\mathrm{CEP})^2$ and lethal radius depends on hardness of the target). Figures for the hardness of objects, especially missile silos, depend on engineering data about the effects of blast overpressure on certain kinds of construction. Many tests of different materials

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[21] See Bunn and Tsipis 1983, for example.

and construction methods were conducted by placing objects of different types at various distances from nuclear explosions (Glasstone and Dolan 1977) during the period when above ground nuclear testing was conducted. Thus, while there are some real "data," the "hardness" values for an adversary's industries, missile silos, and command bunkers are essentially a guess, assuming that their methods of construction and materials are basically like the systems for which one has data. Then, to be "safe," it seems that planners assumed their construction was just a bit better, more resilient than even the best of the ones that have been "tested" (CBO 1978*b*, 46–7). Such may be the case with figures for the hardness of Soviet silos, given as very high numbers (1,000 and 2,000 psi) in the late 1970s and early 1980s. These high numbers, with little basis in "reality," were often repeated without the qualifications attached to them by the Congressional Budget Office when CBO first used the estimates (see CBO 1978*a*, 16).

Donald MacKenzie's work on missile reliability and accuracy demonstrates the softness of these supposedly hard inputs. For instance, the figure used for the overall reliability of US ballistic missiles is a probability that depends on several operations happening in sequence. The land-based missiles must be launched from underground silos and submarine-based missiles must be launched from their submarines. After launch, booster rockets must function successfully, the re-entry vehicle that carries the nuclear warhead must separate from the booster and re-enter the atmosphere, and the nuclear warhead must detonate. High estimates of overall reliability were almost uniformly used in nuclear systems analysis. Yet, despite the importance of missile reliability, there has never been a test of a US nuclear ballistic missile over the same range and gravitational conditions that would be found in an "actual" war. Nor were there many tests of ballistic missiles with "live" nuclear warheads: in testing, ballistic nuclear warheads are removed so that tracking devices can be placed in the missile and re-entry vehicle. Apparently, there was only one test of a nuclear missile that approached operational conditions (although the range and trajectory of the test were not the same as they would be during a nuclear war) in 1962 when a Polaris missile was launched from a submarine and its nuclear warhead detonated at the test range. Air force Chief of Staff Curtis LeMay told members of Congress that even this test "was not under fully operational conditions, we fired one Polaris out in the Pacific with a warhead on it. It was not truly operational. It was modified somewhat for the test" (quoted in MacKenzie 1990, 344). MacKenzie (1990, 343) also notes that because of problems with the Polaris warhead's fusing, "By 1966 it was being estimated by the Livermore nuclear weapons laboratory that between half and three quarters of W47 warheads [used on Polaris missiles] would fail to detonate." Thus, if overall reliability depends on the probability of missile launch, warhead separation, and detonation, the high estimates for reliability given in most systems analysis equations were themselves so optimistic and based on artificial assumptions as to have been nearly fictional. Perhaps such optimistic assumptions were accepted because without them, the deterrence threat became less credible.

Similarly, uncertainty was also elided in the figures for missile accuracy, circular error probable. A supposedly "hard" number, CEP is also based on a relatively few number of artificially simplified tests. Recall that CEP, a distance measured in nautical miles or feet, is the radius of a circle around the target where 50 per cent of the warheads are expected to fall if a large number of test firings were conducted. Some 50 per cent would likely fall outside this radius.[22] Accuracy depends on the gravitational and electromagnetic field of a missile flight path, precise calibration of the inertial guidance system of a weapon, that the re-entry vehicle does not get thrown off course by debris when it re-enters the atmosphere, and so on. The tests that were used to estimate US missile accuracy were conducted on east to west flight paths, over what is known as the Western Test Range, while a US ballistic missile flight against the USSR during the cold war would have gone over the North Pole and over longer ranges—these missiles would experience different gravitational and electromagnetic forces. Moreover, the missiles that are used in these flight tests are specially prepared and "modified" for the tests, so that they are in better working condition than the missiles that actually sit in silos or on submarines (MacKenzie 1990, 344).[23] The missile warhead lands in the test area and the number that is eventually given for CEP of a particular missile type depends on a statistical analysis of a number of these tests. To take uncertainty into account, there are "safety factor" formulas that are apparently used by systems analysts for CEP (MacKenzie 1990, 419). Yet the CEP number is generally taken as a given when inputted into systems analysis calculations.

Ironically, uncertainty, and the sources of uncertainty with respect to CEP were sometimes discussed in great detail by policy modelers and then ignored. For example, the Congressional Budget Office (CBO) produced a number of widely used papers examining US strategic nuclear forces in the 1970s and 1980s. The CBO report was careful to make the problems and uncertainty with the data explicit and also to note that even if more tests were conducted in order to increase confidence in the CEP figures used in the analysis, "actual" nuclear war would be quite different from the tests:

> A very significant consideration for attack planning is the great uncertainty surrounding the actual accuracy of any given guidance technology. This uncertainty results in part from the limited number of tests a missile system undergoes to verify its accuracy potential. Gaining high confidence in estimates of a missile CEP would require a large number of tests for each missile and for each change in its guidance system. Such testing is constrained, however, by the limited resources that can be devoted to the very expensive task of missile testing. Moreover, actual operational performance can be degraded by variable atmospheric conditions and small perturbations in the earth's gravitational field. As a result, actual CEPs can only be estimated within a fairly large range of uncertainty, and any assessment of the damage that an

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[22] Lynn Eden suggested to me that this is an odd locution: it is *circular* error probable although weapons would not fall in a circle but in more of an elliptical pattern.

[23] One could respond that because of these areas of uncertainty, one needs to do more tests. In fact, those who do not want to halt nuclear tests or tests of delivery vehicles and components argue that periodic testing of nuclear weapons and delivery vehicles is necessary to ensure that the weapons will be reliable and that the assumptions about performance are accurate. Yet, even if testing advocates had their way, tests would still be stylized simply because to get the necessary measurements, tests must be conducted under "artificial" and stylized conditions.